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Renewable energy source water pumping systems—A literature review

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A R T I C L E I N F O

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A B S T R A C T

The research developments with renewable energy source water pumping systems (RESWPSs) are reviewed in this paper. The reported investigations are categorized into five major groups as follows: (i) solar photovoltaic water pumping systems (SPWPSs), (ii) solar thermal water pumping systems (STWPSs), (iii) wind energy water pumping systems (WEWPSs), (iv) biomass water pumping systems (BWPSs) and (v) hybrid renewable energy water pumping systems (HREWPSs). More than a hundred published articles related to RESWPSs are briefly reviewed. Additionally, the limitations with RESWPSs and further research needs are described. This paper concludes that renewable energy sources (RESs) play a vital role in reducing the consumption of conventional energy sources and its environmental impacts for water pumping applications.

Contents

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1. Introduction

In India, electrical and diesel-powered water pumping systems are widely utilized for irrigation applications. The continuous exhaustion of conventional energy sources and their environmental impacts have created an interest in choosing RESs such as solar-photovoltaic, solar-thermal, wind energy, producer gas and biomass sources to power water pumping systems [1]. The need for the optimum utilization of water and energy resources has become a vital issue during the last decade, and it will become more essential in the future. The availability of RESs such as solar photovoltaic, solar thermal, wind, biomass and various hybrid forms of energy sources provides good solutions for energy related problems in India [2].

To meet the energy demands and reduce the environmental impact, the idea of integrating RESs such as solar photovoltaic [3,4], solar thermal [5], wind [6], biomass [7] and hybrid forms of energy [8,9] with water pumps has been proposed by many researchers around the world. Earlier reviews reported in this area highlighted the historical development of solar energy water pumping systems for irrigation applications [10,11]. In another review work, Wong and Sumathy [12] consolidated the developments of STWPS, and Delgado-Torres [13] updated the developments of STWPSs. Many research investigations have been reported on RESWPSs during the last decade. However, there is no specific review on RESWPSs. Following the previous cited reviews, the main objectives of this review work can be formulated as follows: (i) a summary of the studies reported with various RESWPSs, (ii) a comparison of various forms of RESWPSs, and (iii) the identification of the future research needs of RESWPSs.

The remaining part of this review contains nine sections. The reviewed articles were categorized as follows: Section 2 (SPWPSs) [16–100], Section 3 (STWPSs) [101–114], Section 4 (WEWPSs) [115–140], Section 5 (BWPSs) [141–144], Section 6 (HREWPSs) [145–147] and Section 7 (comparison of RESWPSs) [148–159]. The current scenario of the RESWPS in India is described in Section 8 [160–162]. Additionally, future research needs with RESWPSs are identified and presented in Section 9 [163–168].

2. Studies on SPWPSs

Photovoltaic energy conversion is one of the best ways to harvest the solar energy [14,15]. Many researchers around the world have investigated the performance of SPWPSs. A summary of the reported investigations in different regions is consolidated in this section.

2.1. Working principle of SPWPSs

SPWPSs consist of solar photovoltaic panels, a motor and a pump, which is depicted in Fig. 1. Depending on the system design, it requires storage batteries and a charge regulator. The motor is chosen according to the power requirement and the type of current output of the system. If the motor uses alternative current (AC), it is necessary to install a direct current (DC) to AC converter. Battery-less SPWPSs are low cost, which requires less maintenance compared to battery powered systems. However, the storage batteries have the advantage of providing consistent performance during lean and off sunshine hours. The addition of a water storage tank in SPWPS is more economical than battery storage backup. The use of solar photovoltaic energy is considered to be a primary resource for the countries located in tropical regions, where direct solar radiation may reach up to 1000 W/m^2. A brief discussion on the studies reported with the performance, the types of motors and pumps, the optimal sizing of the photovoltaic panels, the cooling of the solar photovoltaic panels, the control of SPWPS, economic and environmental considerations are discussed in this sub section.

2.2. Performance of SPWPSs

Table 1 consolidates the review of the reported investigations on the performance of SPWPSs. In related work, Pande et al. [16] designed, developed and tested the performance of SPWPSs for drip irrigation under Indian meteorological conditions. In their system, 900 W photovoltaic arrays and a 800 W DC mono block pump were used. It was reported that SPWPSs can deliver water at

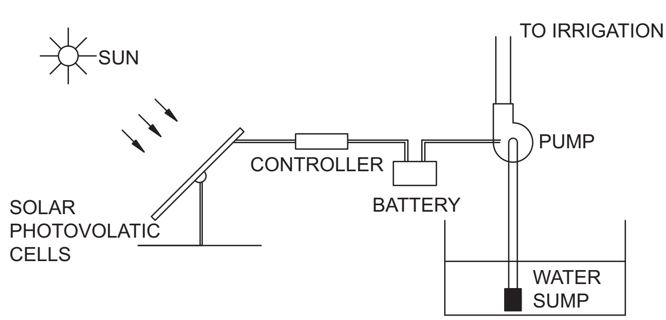

Fig. 1. Layout of SPWPSs.

Table 1
Summary of investigations on SPWPSs.

Authors [Reference]	Country	Applications	Conclusion
Pande et al. [16]	India	Irrigation applications	Pack back period of 6 years was reported
Bhave [17]	India	Irrigation applications	Solar photovoltaic pumping systems are suitable for medium head domestic water pumping applications
Mahmoud and Nather [20]	Egypt	Drip irrigation	Solar photovoltaic water pumps are operating more effective than other traditional water pumping systems
Hamrouni et al. [23]		Domestic water pumping	The performance of the systems is highly affected by ambient parameters such solar intensity, ambient temperature, wind velocity
Meah et al. [25,26]	USA	Domestic water pumping	The solar photovoltaic water pumping systems could reduce the CO_2 emissions considerably over 25 year life time The system is more suitable for rural areas facing shortage of electricity
Chandratilleke and Ho [27]	Singapore	Domestic water pumping	It was concluded that overall efficiency of the photovoltaic water pumping system was improved by better system design and load matching
Badescu [28]		Domestic water pumping	The presence of storage tank will improve the performance of the photovoltaic water pumping systems
Yu et al. [29]	China	Irrigation	Concluded that photovoltaic water pumping is most suitable for grass land conservation
Hrayshat and Al-Soud [32]	Jordan	Water pumping	Identified the potential of solar energy for water pumping
Al Ali et al. [33]	Sadui Arabia	Irrigation	The authors developed automatic irrigation system, which optimize the quantity of water required for irrigation
Mokeddem [35]	Algeria	Irrigation	Directly coupled photovoltaic water pumping systems are suitable for low head irrigation applications
Hamidat [36]	Algeria	Irrigation	Solar photovoltaic water pumping system is suitable for small scale irrigation applications

70–100 kPa pressure at the delivery side with a discharge of 3.4–3.8 l/h through each dripper during different hours of the day. A payback period of approximately 6 years was reported in their work. Similar innovative SPWPSs using a modular centrifugal pump with variable speed and multi activated stages have been developed and tested under Indian meteorological conditions [17]. It has been reported that SPWPSs are more suitable for low and medium head water pumping in areas where grid connected electricity is not readily available. Additionally, they concluded that SPWPSs are economical in operation only during peak sunshine hours. In a similar investigation, Chaurey et al. [18] discussed the field experiences of SPWPSs in India. The system investigated in their work was continuously operated, except for a few loose electrical wire connections, for more than 2 years without a major technical break-down. SPWPSs have been provided as a replacement for the existing hand pumps. The average daily water output of SPWPSs over a month is suitable for a rural water supply to a typical Indian village. They suggested that SPWPSs are feasible for a community of 500 persons if hand pumps are provided as a back-up system. Similarly, the environmental impacts of the SPWPSs are investigated in terms of the clean development mechanism (CDM) [19]. SPWPSs could be of interest under the CDM because they directly reduce the GHG while contributing to sustainable rural development. It was concluded that there is a vast potential of CO_2 mitigation by using SPWPSs in India.

Similarly, in Egypt, Mahmoud and Nather [20] investigated the performance of SPWPSs using batteries for sprinkling and dripping irrigation systems. It has been concluded that SPWPSs can be used efficiently for water pumping in agriculture sectors. The cost of the water pumped by photovoltaic systems is much less than that of water pumped using conventional grid connected and diesel powered pumping methods. They also concluded that SPWPSs can operate more effectively compared to other traditional irrigation systems during potential sunshine hours. The SPWPSs also improve the quality of life and promote socio-economic development in rural area. In related work, Mankbadi and Ayad [21] discussed the performance of small capacity direct SPWPS under the meteorological conditions of Egypt and reported that small capacity direct SPWPSs are most suitable for domestic water pumping applications. In a similar attempt, Qoaider and Steinbrecht [22] investigated the technical feasibility of SPWPS in the New Kalabsha village in the Lake Nasser region of southern Egypt. In their work, the technical design and the life cycle cost of the SPWPSs were calculated. The pumping system was designed to pump 111,000 m^3 of water daily to irrigate 1260 ha and also to power the adjacent households. Their studies concluded that SPWPSs are an economically competitive option for supplying energy to off-grid communities in arid regions compared to diesel generation systems. In a similar investigation, the performance of SPWPS was assessed both theoretically and experimentally [23]. The system consists of a photovoltaic generator, a DC–DC converter, a DC–AC inverter, a submersed type motor-pump and a storage tank. It has been reported that the influence of solar radiation will affect the global efficiency of the pump. The maximum performance of the pump was reached during the middle of the day. However, the performance of the system was degraded due to meteorological parameters such as the solar intensity, the ambient temperature, the wind velocity and the relative humidity. They also confirmed that the theoretical simulation results are close to the experimentally predicted results with acceptable errors.

Kou et al. [24] developed an analytical model for predicting the long-term performance of a direct coupled SPWPS for six different locations in the USA (Albuquerque, New Mexico, Madison, Wisconsin Seattle and Washington) and compared it with the TRNSYS model. It was reported that the model predicts the performance with a root mean square difference of 3–6% compared to the TRNSYS program using TMY weather data. They also reported that the new model proposed in their work can be used for designing and forecasting the long-term performance of SPWPSs over monthly or annual periods under typical US climates. Moreover, a similar performance investigation of SPWPS for remote locations of the United States has been reported [25]. The experimental setup used in their work is illustrated in Fig. 2. It was reported that SPWPSs have a good performance in terms of productivity, reliability, and cost effectiveness. SPWPSs could considerably reduce the CO_2 emissions over their 25-year life span compared to conventional grid connected or diesel powered systems. Additionally, Meah et al. [26] presented the opportunities and challenges of SPWPSs. They suggested that the economy and the reliability of SPWPSs make them more feasible and

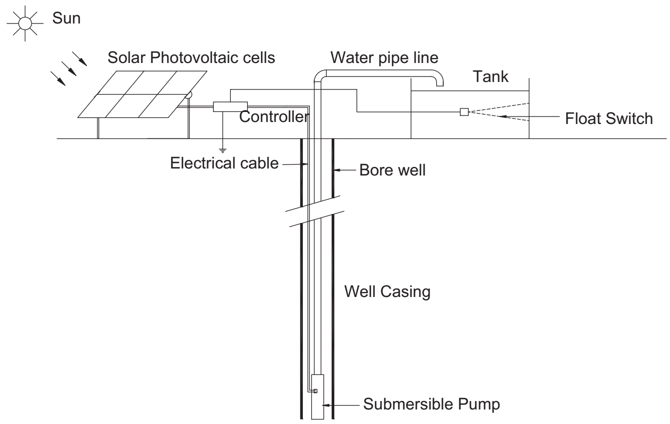

Fig. 2. Layout of solar photovoltaic water pumping system using sumbersible pump [25].

economical in rural locations facing a shortage of electricity. SPWPSs have been proven to be a technically and economically feasible option in developed nations such as the USA, Germany, Australia, etc.

In another work, Chandratilleke and Ho [27] experimentally studied the performance of a 1.14 kW SPWPS using a 860 W centrifugal pump. They also developed a simulation model for validating the experimental results. It was reported that the overall efficiency of the SPWPS is 1.6%, which was found to be lower due to the low energy conversion efficiencies with photovoltaic systems. The simulation results were reported to be closer to the experimental results with acceptable deviations. They also suggest that the overall efficiency of the SPWPS can be improved by good system design and load matching. The storage tank was introduced to improve the stability of SPWPS. In related work, a time dependent SPWPS model consisting of a photovoltaic array, a battery, a storage water tank, a DC motor and a centrifugal pump was developed by Badescu [28]. It has been reported that a storage water tank improves the stability of the pumping operation. The fraction of power supplied by the battery is stored in the form of the gravitational energy of water, which proves that both the battery and the water storage tank increase the operation stability of SPWPSs. Similarly, the performance of a solar powered irrigation system was assessed for sustaining pasture lands in arid regions of North West China [29]. It was reported that SPWPSs for irrigation applications are a cost effective system, which contributes to grassland conservation. They also suggested that solar powered irrigation can create considerable opportunities in promoting local development.

The performance characteristics of SPWPSs in thirteen wells under the meteorological conditions of Jordan were investigated by Hammad [30]. A laboratory SPWPS was developed, and the year round performance parameters such as the daily pumping capacity and the efficiency were analyzed. The monthly pumping factor values were calculated by the experimental results. A design model was established based on the pumping factor as a function of the solar characteristics. In a similar work, a SPWPS using an induction motor pump, which is capable of supplying a daily average of 50 m^3 at 37 m head, was developed by Daud and Mahmoud [31]. The system was installed in a desert well in Jordan, where the average available solar radiation is 5.5 kW h/m^3/day. Long-term field testing of the system showed that the system is reliable and has an overall efficiency exceeding 3%, which is comparable to the other studies reported with highest efficiencies for SPWPS. In a similar attempt, Hrayshat and Al-Soud [32] studied the suitability of SPWPSs at ten different locations in Jordan. They identified four locations (Queira, H-4, H-5, and Taffieleh) where the solar intensity availability is adequate for water pumping applications. Another three regions (include Ras Muneef, Mafraq, and Hasa) have a moderate solar energy source. The remaining three locations (Deir Alla, Baqura, and Wadi Yabis) have poor solar intensity, where SPWPSs are not suitable.

Similarly, in Saudi Arabia, Al Ali et al. [33] developed an automatic solar photovoltaic source irrigation system and tested its performance. Their system consists of controller, control valves, photovoltaic panels, back up batteries and sensors. Their developed system is capable of irrigating fields at a pre-specified time, day of the week and duration. It can also automatically irrigate the field if the soil is dried below a certain moisture level. This type of automated system will optimize the quantity of water required for a particular crop and for a specified area. A similar performance investigation on SPWPSs using a helical pump for a deep well was made under the meteorological conditions of Saudi Arabia [34]. Four different photovoltaic configurations such as 6 serial modules $\times$ 3 parallel rows, 12 serial modules $\times$ 2 parallel rows, 8 serial modules $\times$ 3 parallel rows, and 6 serial modules $\times$ 4 parallel rows were investigated in their work. Their results reported that the 8 serial modules $\times$ 3 parallel configuration provided the optimal energy with a maximum water discharge of 22 m^3/day.

In another work, Mokeddem et al. [35] studied the performance of a direct coupled SPWPS under the meteorological conditions of Algeria over a period of four months. The system performance was monitored under different climatic conditions with two static head configurations. Their system is composed of a 1.5 kWp photovoltaic array, a DC motor and a centrifugal pump. It has been reported that directly coupled SPWPSs are suitable for low head irrigation in remote areas, which are not connected to the national grid and where access to water comes as a first priority issue. Their system runs with low maintenance due to the absence of battery and electronic control. They also reported that directly coupled SPWPSs attain the steady state quickly. Similar investigations on the electrical and hydraulic performance of a small-scale photovoltaic powered irrigation system were performed under the meteorological conditions of the Algerian Sahara region [36]. The SPWPSs used for irrigation applications are depicted in Fig. 3. Approximately sixty SPWPSs were installed in the remote regions to supply water for domestic use and the irrigation of four crops, namely, wheat, potatoes, tomatoes and sunflowers. It has been reported that SPWPSs are suitable for small-scale irrigation in the Algerian Sahara regions. SPWPSs could easily cover the daily water need rates for small-scale irrigation with an area of less than 2 ha. Similarly, Boutelhig et al. [37] studied the performance of SPWPSs with four different configurations (2 parallel (P) $\times$ 2 series (S), 2P $\times$ 1S, 1P $\times$ 2S and 1 module) at different heads between 10 m and 40 m under the meteorological conditions of the Algerian desert area. It was reported that the combination of two photovoltaic array configurations (2P $\times$ 1S) and (1P $\times$ 2S) is suitable to provide the optimum energy. The

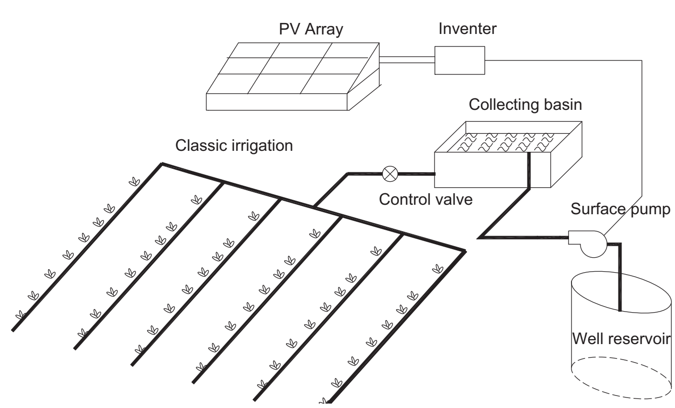

Fig. 3. Schematic layout of photovoltaic irrigtion system [38].

selected photovoltaic configuration pumped a maximum volume of water.

2.3. Types of motors and pumps

The studies reported on different types of motors and pumps used in SPWPSs are discussed in this section. A summary of investigations on motors and pumps are consolidated in Tables 2 and 3, respectively.

2.3.1. Types of motors

Several types of DC motors (i.e., brushed and brushless permanent magnet, variable switch reluctance) and AC motors (synchronous and asynchronous) are available for SPWPSs [11]. The selection of the motor is dependent on the size, the efficiency requirements, the price, the reliability and the availability. DC motors are attractive because they can directly connect to the photovoltaic array. DC motors are not suitable for high-power (above 7 kW) applications, where an AC induction motor with a DC–AC inverter is required. The use of an inverter will lead to additional costs and energy losses. For submersible DC water pumps, maintaining and replacing the brushes of the DC motors requires the pump to be removed from the deep well, which increases the running and maintenance costs and also reduces its reliability and life. Table 2 consolidates the research investigations reported on DC motors used in SPWPSs.

Brushless DC motors were introduced to overcome these drawbacks [38]. The brushless DC motors were used for SPWPSs using helical pumps, and their performance was tested under the meteorological conditions of Australia. It was reported that the efficiency of the system using brushless DC and helical motor pumps varies between 30% and 50%, which is reported to be better than conventional SPWPSs. In similar investigations, Metwally and Anis [39] tested a switched reluctance motor (SRM) for SPWPSs. The motor is supplied by a DC voltage through a switching circuit. The efficiency of the SRMs was reported to be higher than that of DC or induction motors. SRM is cheaper than DC and induction motors, which is the advantage reported in their work. They also concluded that the operating efficiency of SRM is approximately 85% during most of its working time. The matching efficiency between the photovoltaic array and the proposed system approaches 95%. In another work, Singh et al. [40] developed a permanent magnet brushless DC motor drive powered by a solar photovoltaic array coupled with SPWPS. The developed prototype operates satisfactorily with different DC bus voltages. The elimination of the rotor position sensor and current sensors made the system simpler and reduced the overall cost of the drive system. The drive system was found to be suitable to pump water even during lean sunshine hours.

2.3.2. Water pumps used in SPWPS

Vick and Clark [41] compared the performance of a SPWPS using a diaphragm and helical pumps in terms of performance and reliability. The photovoltaic array rated power for typical diaphragm pump systems varies from 75 W to 150 W, whereas the photovoltaic rated power for helical pump systems ranges between 200 W and 1000 W. The reliability of solar photovoltaic powered helical pump systems is better than that of solar photovoltaic powered diaphragm pump systems for pumping depths greater than 30 m. In a related work, Arab et al. [42] presented two mathematical motor–pump models to predict the optimal operating point for SPWPSs based on the experiments. The models are established for centrifugal and positive displacement pumps coupled to DC motors. The experimental data were obtained in a pumping test facility. These models will predict the optimal operating point with the photovoltaic array and the volume flow rate of water. A simplified method was proposed in their work to obtain the parameters of the models to reduce the number of experimental measurements. Similarly, Fiaschi et al. [43] improved the effectiveness of deep well solar pump systems by using centrifugal pumps with a variable speed and a modular number of working stages (divided shaft pump) and compared them with traditional pumps equipped with a fixed number of stages (standard centrifugal pump). The pump shaft used in their investigation is depicted in Fig. 4. The economic analysis results showed the advantage of the divided shaft pump solution in terms of the payback period. The possibility of applying one shaft division to a traditional centrifugal pump, coupled with a variable rotational speed, leads to a more effective use of the daily available solar energy to power a water pumping system.

Hamidat [44] simulated the performance and calculated the pumping cost of a SPWPS using surface pumps under the meteorological conditions of Algeria and reported that surface pumps are cost effective for low total dynamic head applications. In further work, Hamidat and Benyoucef [45] presented two mathematical models to simulate the long-term electrical and hydraulic performances of centrifugal pump and positive displacement pump under the meteorological conditions of Algeria. The performance was calculated using the measured meteorological data of different sites located in the Sahara and the coastline regions of Algeria. It has been reported that the average pumping and total

Table 2
Type of DC motor used in SPWPSs.

Authors [Reference]	Type of DC motor	Advantages
Langridge et al. [38]	Brushless DC motors	The performance of brushless DC motors is found to be better than conventional motors
Metwally and Anis [39]	SRM	SRM are low cost compared to DC motors and also the efficiencies are higher than DC motors
Singh et al. [40]	Permanent magnet brushless DC motors	This type of motors is quite suitable even during low power caused during low sun shine hours

Table 3
Type of water pumps used in SPWPSs.

Authors [Reference]	Type of pump	Outcomes
Vick and Clark [41]	Diaphragm and helical pumps	Diaphragm performs better than helical pumps
Fiaschi et al. [43]	Divided shaft pump and standard centrifugal pump	Divided shaft pumps performed better than standard centrifugal pumps
Hamidat and Benyoucef [45]	Centrifugal and positive displacement pump	The efficiency of the positive displacement pumps are higher compared to centrifugal pumps Energy losses of positive displacement pumps are less compared to centrifugal pumps

efficiencies of the positive displacement pumps are higher for a large range of the total head compared to the centrifugal pumps. The average energy losses of the positive displacement pumps are lower than the centrifugal pumps, especially for high total heads. The average volume of water pumped by positive displacement pumps is higher compared to that of the centrifugal pumps.

2.4. Cooling of solar photovoltaic panels

The solar photovoltaic cells become heated during energy conversion and also due to the effect of solar radiation. The performance of the system is highly affected by heat generation. Thus, it is essential to maintain the temperature of photovoltaic cells to attain the maximum power output [46]. Many investigations have been reported with cooling of solar photovoltaic panels [47–49].

To attain a good performance of SPWPSs, Abdolzadeh and Ameri [50] made an attempt by spraying water over the front panels of photovoltaic panels. It has been reported that the solar photovoltaic efficiency, the subsystem efficiency and the total efficiency were improved by 3.26%, 1.40% and 1.35%, respectively, at a head of 16 m. They also reported that a maximum solar photovoltaic efficiency of approximately 13.5% was achieved in their work. In similar work, Kordzadeh [51] studied the performance of a SPWPS with a film layer of water over the cell surface. The performance of the system was evaluated under the meteorological conditions of Kerman city in Iran. It has been reported that the performance of the SPWPS was increased significantly by providing a film layer of water over the photovoltaic cells. A recent review of work on cooling of solar photovoltaic panels reported that carbon nano-tubes and a high conductive coating provide the best cooling performance for solar photovoltaic panels [53].

2.5. Optimal sizing of SPWPS

The high initial investment of solar photovoltaic source irrigation systems makes it necessary to dimension the photovoltaic panels as accurately as possible [53]. In this subsection, the studies reported on the optimal sizing of SPWPSs are consolidated briefly. The uncertainties in solar radiation measurements will greatly influence the sizing of solar photovoltaic panels. Thus, an accurate method of solar intensity measurement is required for an accurate sizing of photovoltaic panels [54]. Table 4 consolidates the research investigations on the optimal sizing of SPWPSs.

Cuadros et al. [55] presented a design procedure to estimate the required dimensions of photovoltaic panels to power a pumping system for drip irrigation of an olive tree orchard in Spain. The method presented in their work involves three main stages. In the first stage, the irrigation requirements of the specific estate according to the characteristics of its soil-type and climate are estimated. In the second stage, a hydraulic analysis of the pumping system was made according to the depth of the aquifer and the height needed to stabilize the pressure in the water distribution network. In the final stage, the peak photovoltaic power required to irrigate a 10 ha sub-plot of the estate was found while considering the overall yield of the photovoltaic-pump-irrigation system. In similar theoretical optimization work, the size of an autonomous SPWPS was optimized and compared with

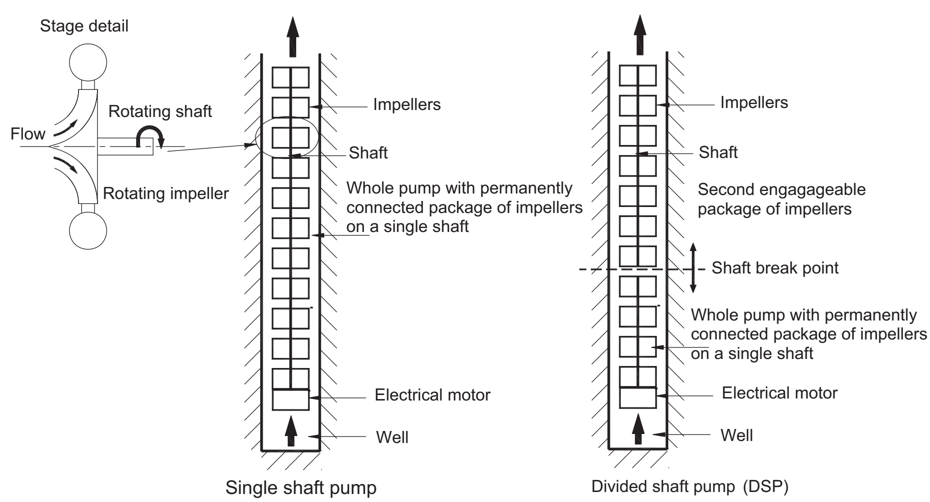

Fig. 4. Schematic layout of pump shafts [43].

Table 4
Sizing of photovoltaic systems.

Authors [Reference]	Optimization technique	Conclusions
Cuadros et al. [55]	Conventional	The size was optimized in three stages. In the first stage the irrigation requirements were estimates followed by hydraulic analysis of water pumping system according to the head. The final state estimated the power requirement for irrigation
Kaldellis [56,57]	Conventional	The optimized water pumping system can able to cover the both domestic electricity requirements and for water pumping requirements
Firatoglu and Yesilata [58]	Multi-step	The results showed that better system performance with less photovoltaic ares can be obtained by accurate selection of array configuration
Bakelli et al. [60]	Loss of power supply probability	An improved performance was reported with optimized solar photovoltaic water pumping systems
Arab et al. [61]	Loss of load probability	It has been concluded that size of photovoltaic cell depends on availability of solar radiation
Betka and Attali [65]	Optimal control theory	It has been reported that it is possible to reduce the machine losses, field oriented control, maximization of power point tracking
Hamidat and Benyoucef [67]	Load losses probability	The results showed that the performance of the system depends on total pumping head and power output of the array

experimental values [56,57]. The experimental test setup used in their work for water pumping and electrical lighting is illustrated in Fig. 5, which is used to power lights and a water pump. It has been reported that a properly optimized photovoltaic pumping configuration of 610 W is capable of covering both the electricity (2 kWh/day) and the water requirements (maximum 400 lph) for a large variety of remote consumers. They also concluded that SPWPSs are an attractive and environmentally friendly option with low maintenance requirements, which significantly contributes to the satisfaction of water consumption needs in remote areas facing a scarcity of electricity.

Firatoglu and Yesilata [58] used a simplified multi-step optimization technique to improve the utilization of solar energy in a direct-coupled SPWPS for the meteorological conditions of Turkey. The optimal solution was obtained by using the available meteorological data for the design-site and the manufacturer data for the system components. The performance was predicted for the 16 years between 1985 and 2001. The tilt angle of the photovoltaic array was optimized by the linear search method, and the solar radiation interval was optimized by the utilizability method. The number of photovoltaic panels and their optimal electrical configuration in the array were determined by a nonlinear search method based on a statistical parameter. It was reported that the system performance was good with a lower photovoltaic array area. Similarly, Jafar [59] developed an accurate procedure to model a SPWPS. Their developed model predicts the volume flow rate within 8% of the measured values. Although the deviation is lower, the fluctuations in the solar radiation and the module temperature measurements will influence the model predicted results.

Bakelli et al. [60] optimized the size of a SPWPS using a water storage tank in terms of the loss of power supply probability (LPSP) for the reliability of the system and the life cycle cost (LCC) for an economic evaluation for the meteorological conditions of Ghardaia, Algeria. The SPWPS used in their work is depicted in Fig. 6. The input data used in their work to optimize the SPWPS were the hourly solar radiation, the ambient temperature, the water requirements and the specifications of the system devices. The optimization methodology used in their work proposed the procedures based on water consumption profiles, the total head,

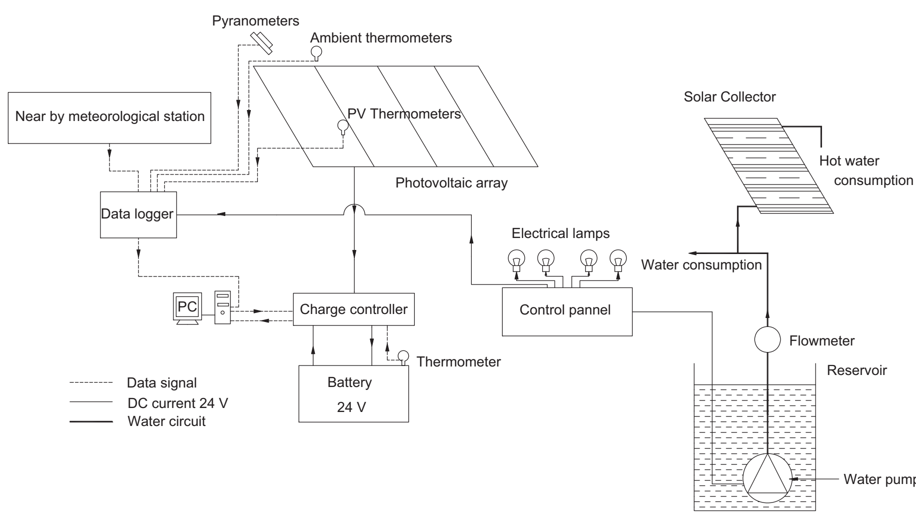

Fig. 5. Schematic layout of solar thermal water pump [57].

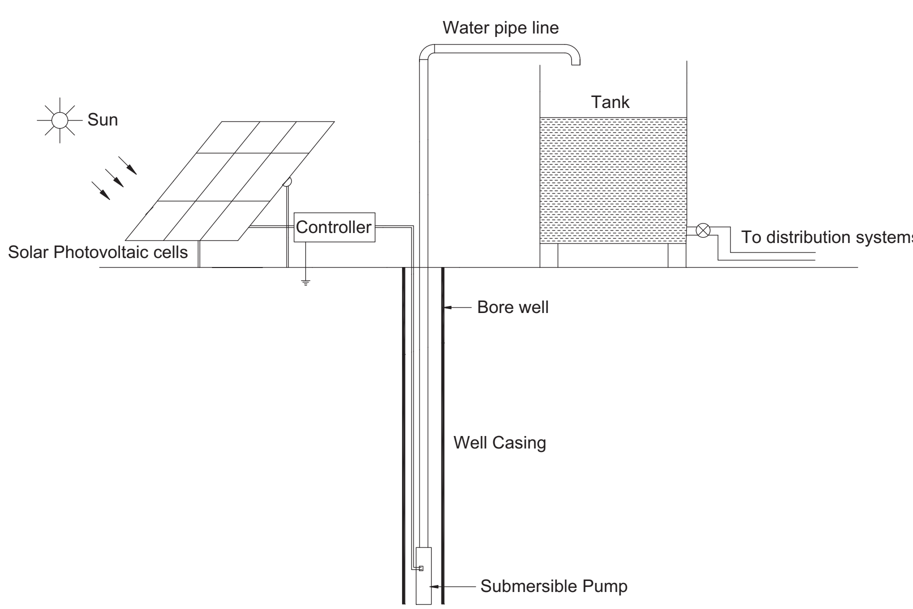

Fig. 6. Schematic layout of photovoltaic water pumping system using storage water tank [60].

the tank capacity and the photovoltaic array peak power. It was reported that the LCC for a head of 6 m compared to other heads of 14 m and 26 m led to a desired LPSP of 5%, 1%, 0.3% and 0%, respectively. An improved system performance was reported in their case study. In a similar optimization approach, Arab et al. [61] used the loss of load probability method to optimize the size of SPWPSs. The loss of load probability is defined as the ratio between the number of hours of the water deficit and the number of hours of consumption. It has been reported that size of the photovoltaic cell depends on the availability of solar radiation in that particular location.

Martire et al. [62] presented an accurate prevision method for sizing the SPWPS (composed of non-linear components such as a centrifugal pump, a three phase induction motor, a switching converter and a photovoltaic generator) and compared it with experimental methods. It has been concluded that the simulation results are closer to the experimental values with acceptable errors. The model presented in their work is more flexible for the optimal design of new SPWPS using different types of pumps with few electromechanical considerations. In a similar approach, Protogeropoulos and Pearce [63] developed system sizing charts for a solar operated low-power and low cost submersible diaphragm pump for medium head applications. The instantaneous water flow versus the head characteristics were functions of the global irradiance on the array plane. The photovoltaic array power varied between 55 Wp and 220 Wp and both voltage modes were examined. The hydraulic efficiency was also calculated with respect to the equivalent head. The daily operation charts were obtained with reference to the instantaneous pump performance in combination with daily irradiation profiles and the pump starting and stopping characteristics. Their developed charts are used for the system sizing of SPWPSs. The results showed that new generation direct solar-powered pumping systems will minimize the initial investment and eliminate the need for battery storage.

In a similar attempt, Glasnovic and Margeta [64] developed an optimization model to size SPWPSs, and it has been tested in two areas of Croatia. In their work, the objective function was defined with reference to the SPWPS, the local climate, the boreholes, the soil, the crops and the method of irrigation. It was reported that the electrical power of the photovoltaic generator obtained by the new optimization technique was smaller than that of the conventional optimization method. In another work, Betka and Attali [65] optimized a SPWPS based on optimal control theory. The optimization problem consists of maximizing the daily pumped water quantity by the optimization of the motor efficiency for every operation point. The proposed structure in their work allows the simultaneous minimization of the machine losses, field-oriented control and the maximum power tracking of the photovoltaic array, which will be attained based on multi-input and multi-output optimal regulator theory.

Ghoneim [66] developed a computer simulation optimization model for a direct coupled SPWPS under the meteorological conditions of Kuwait. The direct coupled SPWPS consists of a photovoltaic array using amorphous silicon solar cell modules, a DC motor, a centrifugal pump, a storage tank that serves a purpose similar to that of battery storage and a maximum power point tracker to improve the energy conversion efficiency of the photovoltaic system. In their study, the pumped water was used for domestic needs in remote areas of Kuwait. Their simulation program consists of modeling a photovoltaic array with the maximum power point tracker and component models for both the DC motor and the centrifugal pump. The size of the photovoltaic array, the orientation and the pump–motor–hydraulic system characteristics were varied to achieve the optimum performance. It was concluded that the cost of the optimized SPWPS was less expensive than the cost of the conventional fuel system. The reduction in cost of photovoltaic modules in the future makes SPWPSs a more feasible option. In a similar analytical work, Hamidat and Benyoucef [67] developed a systematic procedure to size SPWPSs using a storage tank by using the load losses probability. The results showed that the performance of the SPWPS depends significantly on the total pumping head and the power output of the photovoltaic array. They also concluded that SPWPSs are a good option for domestic water pumping compared to conventional energy based water pumping methods. The simulation model developed in their work was accepted for four different locations in Algeria (Algiers and Oran in the north and Bechar and Tamanrasset in the south).

Ould-Amrouche et al. [68] developed a mathematical model of a SPWPS using positive displacement pumps and its CO_2 mitigation potential. The experimental results were used to validate the analytical model developed. The results predicted by the model are close to the experimental values. It was reported that CO_2 emissions can be reduced by the use of water pumping facilities powered by a solar photovoltaic array instead of diesel fuelled generators. They also showed that the dissemination of photovoltaic water systems not only improves the living conditions in remote areas but also protects the environment. In another work, Corrêa et al. [69] optimized the size of standalone SPWPSs and also reduced the payback period. They optimized the efficiency of photovoltaic energy conversion using the maximum power point tracking algorithm and by reducing the losses in the induction motor. The improvements in their work can contribute to the feasibility of water pumping applications in remote areas where electrical energy is not readily available by reducing the initial cost and its payback time. Similarly, Campana et al. [70] developed a dynamic modeling tool for designing SPWPSs with special consideration of the water demand. The site chosen in their study was Xining, China. Both AC and DC water pumps with fixed and two-axis photovoltaic array tracking were analyzed. The results showed that the AC pump driven by the fixed photovoltaic array is the most cost-effective solution. Karim and Rahman [71] studied the cost-effective suitability of SPWPS in Bangladesh. It was reported that an increase in the utilization factor of SPWPSs results in a reduction of the unit cost. Thus, the utilization of solar photovoltaic cells can be improved by connecting the system with other domestic uses, which are not linked with irrigation applications.

The investigation of the performance consolidated in this section around the world attempted an analytical approach to optimize the size and the tilt angle of SPWPSs. However, the conventional analytical methods involve more assumptions and complicated equations. To reduce the complications, artificial intelligence (AI) techniques were introduced to optimize the size of photovoltaic panels [72]. However, limited investigations have been reported on the use of AI technique for the sizing of SPWPSs, which requires further investigation. To maximize the efficiency of the photovoltaic power output, the tilt angle of the photovoltaic panels must be optimized. Many research investigations have been reported on the optimization of the tilt angle of photovoltaic panels for different meteorological conditions around the world [73,74].

2.6. Control of SPWPS

It is essential to control the operation of SPWPSs to achieve the maximum performance. Table 5 illustrates the various control methods reported by the researchers around the world. Sallem et al. [75] developed an intelligent algorithm to improve the effectiveness of the water pumping system, which makes decisions on the interconnection modes and instants of SPWPSs, such as the battery, the water pump and the photovoltaic panel. It was

Table 5
Control of photovoltaic water pumping systems.

Authors [Reference]	Type of control	Conclusions
Sallem et al. [75]	Intelligent algorithm	The algorithm implementation the approach extends the pumping period of 5 h/day
Mazouz and Midoun [76]	Fuzzy logic technique	The solar photovoltaic energy utilization for water pumping will improve the performance and photovoltaic efficiency
Zaki et al. [77,78]	Programmable logic circuit	It controls the maximum power point tracking, pumping system operation, system power balance and battery and charge-discharge monitoring
Terki et al. [79]	Proportional–integral, fuzzy logic speed controller	Fuzzy logic controllers showed improved performance compared to conventional PI controller
Benlarbi et al. [80]	Fuzzy optimization	Fuzzy optimization maximize the global efficiency by increase the drive speed and the water discharge rate
Fernández-Ramos et al. [81]	Standard frequency converter and PLC	The addition of standard frequency converter and PLC will avoid the stopping of the system when the solar intensity falls suddenly

reported that the effectiveness of SPWPSs depends on the ability between the generated energy and the volume of water pumped. The decision is made by fuzzy rules on the basis of the photovoltaic panel generation forecast for the day considered, on the load required power, and by considering the battery safety. The algorithm aims to extend the operation time of the water pump by controlling a switching unit, which links the system components with respect to multiple objective management criteria. The algorithm implementation extends the pumping period for more than 5 h per day, which gives a mean daily improvement of 97% of the water pumped volume. Mazouz and Midoun [76] proposed a novel fuzzy logic technique for the identification of the maximum power point, which is used to generate the cyclic ratio to operate the switcher with the maximum power output of a photovoltaic array. The application of fuzzy logic in the field of solar photovoltaic energy utilization for water pumping will improve the performance and the photovoltaic efficiency. The experimentally obtained results confirmed that a fuzzy controller is suitable for the optimization of a water pumping system.

Zaki et al. [77,78] used programmable logic circuits (PLC) to control the efficiency of SPWPSs for irrigation applications. In their work, PLC controls the maximum power point tracking, the pumping system operation control, the system power balance, and the battery charge–discharge monitoring and control. Two photovoltaic arrays were used in their work, which are interchangeable to gain high reliability. One photovoltaic array was used for irrigation, and the other was used for lighting applications. The first photovoltaic array feeds the pumping system, and its maximum power operating point is adjusted by the DC–DC, converter connected to the DC motor terminals. The other photovoltaic array is used to power the lights and the household equipment. The battery charger takes the role of controlling its operation to the maximum power line. The irrigation area can be increased by adding a third photovoltaic generator module with a motor pump. Terki et al. [79] reported the performance of a permanent magnet brushless DC motor controlled by proportional–integral (PI) and fuzzy logic speed controllers. It has been reported that the fuzzy logic speed controller showed an improved transient response compared to conventional PI controllers for non-linear control systems.

In a similar approach, Benlarbi et al. [80] presented an on-line fuzzy optimization of a SPWPS driven by three different motors such as an excited DC motor, a permanent magnet synchronous motor, or an induction motor coupled to a centrifugal pump. The fuzzy optimization procedure aims to maximize the global efficiency by increasing the drive speed and the water discharge rate of the coupled centrifugal pump. They confirmed the suitability of using the fuzzy logic procedure as a standard optimization algorithm for photovoltaic water pumping drives. They also reported that a permanent magnet synchronous motor is a good choice for the SPWPS drive because DC motors require periodical maintenance. However, an induction motor is technically a competitive choice. Similarly, Fernández-Ramos et al. [81] improved the performance of SPWPSs by using a standard frequency converter and PLCs. It has been proved that the addition of a standard PLC to a SPWPS based on standard frequency converters will avoid the stopping of the system during sudden decreases of the solar radiation. In another work, Benghanem and Arab [82] reported the performance of a domestic SPWPS installed in remote areas of Algeria. Due to high cost of the setup, the maintenance and the performance monitoring of a large number of SPWPS, they developed a universal data acquisition system for monitoring the performance and optimizing the size of SPWPSs located in different remote regions of Algeria.

2.7. Economic and environmental aspects of SPWPS

The two general ways to prove the feasibility of SPWPSs are economic and environmental aspects. The economic and environmental aspects of SPWPSs are discussed in detail in this subsection [83].

2.7.1. Economic aspects of SPWPSs

The total investment required to install SPWPSs includes the cost of components such as panels, inverters, electrical cables, pumps and pipes [84]. The cost of the photovoltaic panels is high compared to the other energy generating devices, such as diesel engines and electrical motors. However, SPWPSs do not require running costs during their lifetime except for the maintenance cost. In contrast, the grid connected and diesel powered water pumping systems require high running and maintenance costs. After the payback period, the SPWPSs will run without a running cost. SPWPSs were identified as the most feasible option compared to conventional grid connected and diesel powered systems for the rural areas facing a shortage of electricity [26].

2.7.2. Environmental impacts of SPWPSs

Photovoltaic systems consume a large amount of energy and also emit GHG during manufacturing, assembly, balance of system (BOS), transportation, installation and recycling. The global warming potential of photovoltaic systems is approximately 10 times lower than that of a coal-fired plant, but it is 4-times higher compared to a nuclear power plant and a wind turbine power plant [85]. The environmental impacts of the SPWPS are assessed in terms of the energy payback time (EPT) and the GHG emission rate. The EPT and rate of GHG emissions are estimated by the following equations [86]. Photovoltaic systems have an EPT of less than 5 years.

$$\mathrm{EBT} = \frac{E_{\mathrm{input}} + E_{\mathrm{BOS}}}{E_{\mathrm{output}}} \tag{1}$$

$$GHG = \frac{GHG_{PV} + GHG_{BOS}}{E_{LCA-Output}} \quad (2)$$

A life cycle assessment of five different types of photovoltaic panels was investigated, and they were compared in terms of the EBT and the GHG emission rate [87]. The five photovoltaic modules investigated in their work are mono-crystalline, multi-crystalline, amorphous silicon, cadmium telluride thin film and copper indium selenide thin film. The EPT and the GHG emission rate of five different types of photovoltaic systems are compared in Table 6 [88–92]. Among the five photovoltaic modules, the cadmium telluride thin film photovoltaic system has the best environmental benefits, whereas the silicon based photovoltaic module has the worst performance. The environmental impacts of the photovoltaic systems can be reduced by improving the production processes, recycling of module materials and reducing the thickness of the panel and other raw materials.

2.8. Limitations of SPWPSs

The following major limitations of SPWPSs are identified:

i. The performance of the SPWPSs is significantly affected by fluctuations in the solar intensity [93,94].
ii. SPWPSs have not become commercially popular due to improper financing schemes [95].
iii. During energy conversion in photovoltaic cells, heat is generated in the photovoltaic cells, which affects the output of the photovoltaic cells [96].
iv. Dust accumulation over the solar photovoltaic panels can lose up to 30% of the energy output within a few weeks of installation [97,98].
v. Effective heat sinks must be developed for extracting the heat from SPWPSs.
vi. The ambient relative humidity and wind velocity will affect the performance of the SPWPS [99].
vii. Solar photovoltaic panels produce global warming during their life cycle [100].
viii. The efficiency of photovoltaic energy conversion is very low.

Table 6
Environmental impacts of SPWPSs.

Authors [Reference]	Type	EPT (years)	GHG emissions ($g\text{-}CO_2$-eq./kW h)	Life time (years)
Ito et al. [88]	Mono crystalline	2.5	50	N.A
Ito et al. [88]	Multi crystalline	2.0	43	N.A
Raugei et al. [89]	Cadmium telluride	1.5	48	20
Raugei et al. [89]	Copper indium selenide	2.8	95	20
Pacca et al. [91]	Amorphous silicon	3.2	34.3	20

3. Studies on STWPSs

Many investigations have reported the utilization of STWPS applications, which, in 2000, were reviewed by Wong and Sumathy [12]. Later, the development status was updated by Delgado-Torres [13]. However, STWPSs are still not commercialized due to their low conversion efficiency. In this paper, a brief overview of STWPSs is described in this section.

3.1. Working principle of STWPSs

The essential components of STWPSs are depicted in Fig. 7. In a STWPS, the solar thermal energy from the sun is converted to mechanical energy. In solar thermal energy conversion, flat plate solar collectors including concentrators can be utilized to pressurize the fluid. During pressurization, the temperature and the pressure of the fluid increase. This high pressure fluid can be either utilized directly in thermodynamic cycles (such as Rankine, Brayton or Stirling cycles) or utilized indirectly by a secondary working fluid to convert into mechanical energy [13]. The converted mechanical energy can be utilized to operate a pump. The main advantages of STWPSs are their low cost and that they are maintenance free and without mechanical moving components.

3.2. STWPSs based on vapor power cycles

In this subsection, the performance of a few investigations on STWPSs is consolidated briefly. The summary of various investigations reported on STWPSs is consolidated in Table 7.

Sumathy et al. [101,102] developed a STWPS using a solar vapor generator storage tank, as illustrated in Fig. 8. The system with a 1 m^2 aperture area of a flat plate solar collector and pentane as the working fluid was able to lift 336 l/day, 250 l/day and 170 l/day at 6 m, 8 m and 10 m, respectively, with a global efficiency between 0.12% and 0.14%. The size of the vapor storage tank was optimized

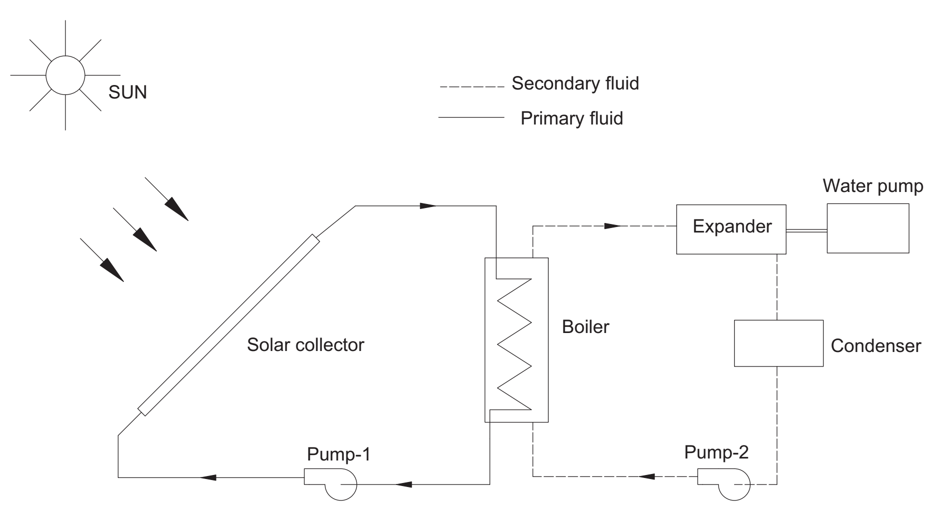

Fig. 7. Layout of solar thermal water pumping system [2].

to improve the performance of the system [103]. In further work, a simple flat-plate collector with a collector area of 1 m^2 was used to pump water ranging from 700 l/day to 1400 l/day depending upon a head of 6 m to 10 m [104]. Such pumping systems can achieve an efficiency of approximately 0.42–0.34%. The heating time and the condensation time of the solar thermal water pump were optimized to improve the performance of the solar thermal pump [105]. It has been reported that the quantity of ethyl ether controls the heating time, and the preferred condensation time can be obtained by optimizing the surface area of the cooling coil. Wong and Sumathy [106] studied the performance of a solar thermal water pump working with *n*-pentane and ethyl ether as working fluids. It was reported that the efficiency of the pump working with ethyl ether is approximately 17% higher than that of *n*-pentane at a discharge head of 6 m. The cost of ethyl ether is low compared to *n*-pentane, which is another advantage of using it in STWPSs [12].

Fenton et al. [107] developed and evaluated the performance of a solar thermal power irrigation system under the meteorological conditions of the USA. They investigated the performance of major subsystems such as the collector array, the thermal storage, and the organic working fluid based Rankine cycle heat engine for the period of summer months. During the summer months, the daily collector array efficiency (based on direct solar radiation normalized in the plane of collector aperture) was nominally 25%, and the heat engine rankine cycle efficiency was 15%. These conversion efficiencies coupled with the numerous system losses resulted in an overall efficiency of nearly 3% on clear summer days. Electrical parasitic losses reduced the net power output of the system by approximately 20% on clear days and greater amounts on other days. Spindler et al. [108] developed and tested the performance of a solar thermal power water pump using R113 with a boiling point at 1.013 bar of 47.6 °C as the working fluid. In their system, a 2 m^2 parabolic collector was used. Their system was developed by Chandwalker in Hybderabad, India and tested in Germany. The refrigerant passes through the following changes of state in a closed loop: evaporation of liquid R113 using solar energy, vapor superheating using solar energy to produce high-pressure vapor, expansion of the high-pressure vapor with the output of the mechanical energy to operate the water pump and the feed pump, condensation of R113 vapor at low pressure using pumped water and pressurization of the liquid R113 in the feed pump. The pressure inside the system was maintained below the atmospheric pressure. During operation, the maximum pressure was maintained below 3 bar, which makes the system much safer than conventional high-pressure systems.

3.3. Solar assisted methyl hydride water pumping systems

The metal hydride-based water pumping systems (MHWPSs) were developed during the late 1970s [109]. The working principle of MHWPSs is based on the thermal sorption and desorption of hydrogen, which causes pressure changes inside the system, which are utilized for water pumping. The hydride subsystem consists of a reactor bed with heating and cooling coils and a bellow. Heat is supplied to desorb the hydrogen from the bed to build up pressure inside the bellow to expand. After completion of the desorption process, the heat supply is stopped, and a part of the pumped water is circulated for cooling. The cooling of the bed causes the absorption of hydrogen from the bellow, which makes the pressure drop and the bellow contract. After the absorption process is completed, the heat supply is started again, and the cycle repeats [110]. In related work, Das and Gopal [111] simulated the performance of solar assisted MHWPSs. Their study showed that it is possible to pump 3000 l of water in a day over a height of 15 m using a 1 m^2 solar collector area, depending on the design and operating conditions. The maximum overall thermal efficiency of the solar assisted MHWPSs was found to be approximately 1.5%.

3.4. Limitations of STWPSs

The major limitations of STWPSs are as follows:

i. The thermal conversion efficiency of STWPSs is very low [112].
ii. The cost of working fluids such as metal hydride and *n*-pentane is much higher, which makes the system unfeasible [113].
iii. Some working fluids used in STWPSs (such as R11 and R113) is environmentally unsafe [114].
iv. STWPSs will take more time to attain steady state compared to photovoltaic systems.
v. STWPSs require more land space for tracking the solar radiation.
vi. The system should be leak proof to avoid loss of the working fluids.
vii. STWPSs are not suitable for pumping a large quantity of water under high heads.

4. Studies on WEWPSs

The pumping of water through small wind powered systems has become popular due to its flexibility over other mechanical systems and its advantage of using the spare electricity for other applications [5].

4.1. Working principle of WEWPSs

In WEWPSs, a wind powered rotor is coupled to a synchronous generator with permanent magnets, which convert the wind energy into electrical power energy. Synchronous generators are most commonly designed for the charging of storage batteries. The asynchronous generators are typically found in large wind turbines. The generator is then coupled to a common induction

Table 7
Solar thermal water pumping systems.

Authors [Reference]	Country	Working fluid	Conclusions
Sumathy et al. [101,102]	India	Pentane	The results reported that the pump can able to pump 336 l/day 250 l/day, 170 l/day at 6 m, 8 m, and 10 m, respectively
Wong and Sumathy [104]	India	Ethy ether	The surface area of the cooling coil needs to optimize to improve the performance
Spindler et al. [108]	Germany	R113	During operation, the pressure inside the system was maintained below 3 bar to make the system to operate in safer conditions
Prasad et al. [110]	India	Methyl hydride	Prototype model was developed
Das and Gopal [111]	India	Methyl hydride	The system can able to pump 2000 l of water in a day to a height of 15 m

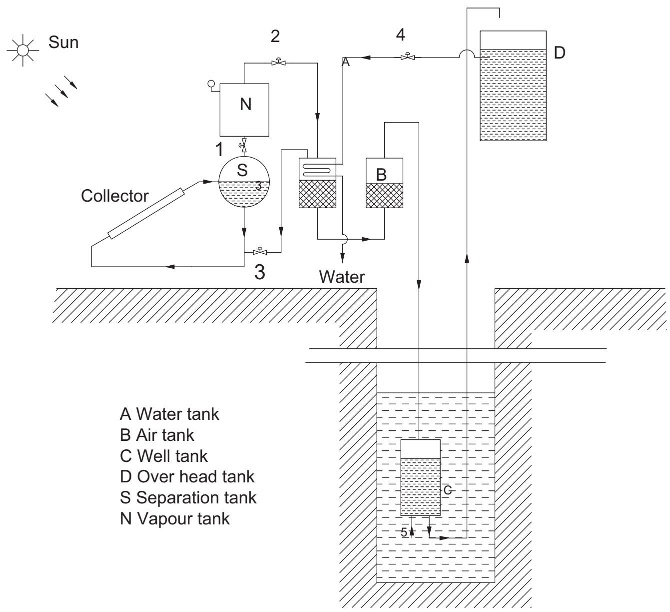

Fig. 8. Schematic layout of solar thermal water pump [101,102].

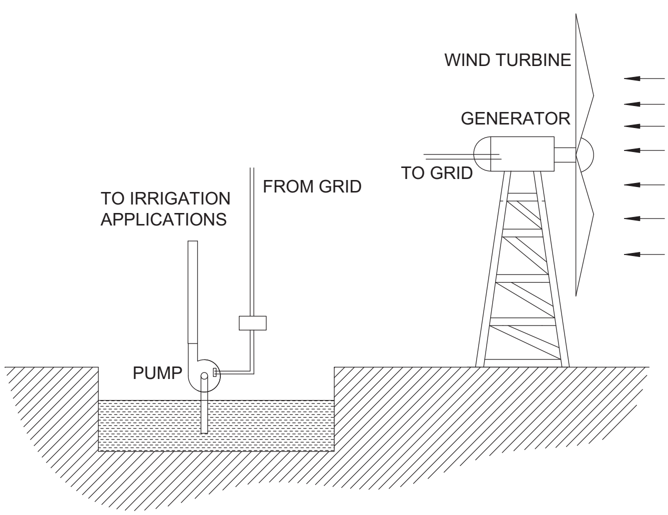

Fig. 9. Layout of wind energy based water pumping system.

motor, which drives a centrifugal pump for water pumping. The essential components of WEWPSs are illustrated in Fig. 9.

4.2. Performance of WEWPSs

Wind energy is one of the most hopeful renewable energy sources for water pumping applications. In India, wind power generation has gained a high level of attention and acceptability compared to other renewable energy sources [115,116]. India has highest wind energy potential after the USA, Germany, Spain and China. The investigations reported on the suitability of wind energy based water pumping systems are briefly consolidated in this subsection. The summary of investigations on wind energy based water pumping systems is tabulated in Table 8.

In 1983, Panda et al. [117] estimated the water pumping cost of systems under Indian meteorological conditions. The cost per m^3 of irrigation water supplied by the most economic wind turbine irrigation system was found to vary between 38 paise and 71 paise in Delhi, India during the month of October 1983. However, the cost of water pumping escalated during the last three decades. Similarly, in 1984, Parikh and Bhattacharya [118] studied the feasibility of wind powered water pumping systems for irrigation applications under Indian meteorological conditions. It was reported that wind energy based water pumping systems are best suited for irrigation applications for Indian meteorological conditions. Additionally, Sinha and Kandpal [119] estimated the cost of irrigation water for two shallow-well, water-pumping wind turbine designs for three locations: Indore, Chennai and New Delhi in India. An empirical relationship of the variation of the overall efficiency of the wind turbines with the wind speed was developed. They suggested that wind turbine irrigation systems are economically preferred alternative technologies for water pumping under India meteorological conditions.

Shi et al. [120] presented several stages in developing WEWPSs for the meteorological conditions of China during the year 1989. Their investigation study reported that China has a large potential for wind energy sources in the North West and South East seashore regions, which requires more wind energy water pumps for irrigation applications. Similarly, Harries [121] presented a historical review of the design, development, manufacturing and field-testing experiences of wind energy source water pumping systems for remote areas of Kenya. A local manufacturer in Kenya was involved in the manufacture of WEWPSs and successfully installed approximately 300 wind pumps in rural regions of Kenya for domestic and agricultural water pumping applications. In a related work, Mohsen and Akash [122] studied the potential of WEWPSs under the meteorological conditions of Jordan at eleven different locations. Their results reported that three locations (Mafraq, Ras Muneef, and Aqaba) were promising locations for wind turbines. Another three locations (H-5, Irbid, and Ma'an) have moderate wind velocities. The remaining wind sites (which include tt-4, Amman, Queen Alia's Airport, Shoubak, and Deiralla) were found to be unattractive due to their lower wind energy potential.

In a similar work, Suleimani and Rao [123] studied the performance of wind powered water pumping systems under the meteorological conditions of the Sultanate of Oman. It was concluded that wind energy can be used successfully for pumping the groundwater in remote locations of Oman, where adequate wind energy resources are available. In their work, a carefully designed highly efficient modern irrigation system was used for the effective utilization of the wind powered water-abstraction system. The storage of an adequate quantity of groundwater is essential for irrigating crops during low-wind conditions. Excess power from the wind turbine was used to drive booster pumps to circulate the stored water in low wind velocity conditions. Depending on the requirements, water can be pumped to an overhead storage facility and can then be provided by gravity. A hybrid system combining wind–solar photovoltaic–diesel power generator elements can be used to power water pumping systems in remote locations of Oman.

Lara et al. [124] assessed the performance of WEWPSs. It has been reported that the turbine blades could convert 35% of the kinetic energy available in the wind into rotational energy. From this energy, 51% could be lost by the electrical components of the system (such as rectifier, batteries, and inverter). As a maximum, only 17% of the energy available in the wind can be available for water pumping applications. A considerable amount of energy is lost during the wind energy conversion process. Thus, they suggest developing a new configuration to avoid such losses in wind pumping systems. The kinetic energy storage in the wind turbine pumping system before connecting it to its load is a vital issue for successful start-up. To overcome this drawback, a sufficient amount of kinetic energy is required in the wind turbine for easy startup [125]. The kinetic energy stored in the wind turbine can tackle the losses in the WEWPSs.

Table 8
Wind energy water pumping systems.

Authors [Reference]	Country	Investigation
Panda et al. [117]	India	Estimated the cost of wind powered water pumping systems
Parikh and Bhattacharya [118]	India	Feasibility of wind powered water pumping systems
Sinha and Kandpal [119]	India	Estimated the cost of water pumped using wind energy at three different locations
Shi et al. [120]	China	Development of wind powered water pumping systems in China
Harries [121]	Kenya	Field testing experience of wind energy powered water pumping systems
Mohsen and Akash [122]	Jordan	Estimated the wind energy potential
Suleimani and Rao [123]	Oman	Performance of wind energy powered water pumping systems
Lara et al. [124]	Chile	Estimated the losses in wind powered water pumping systems
Badran [126]	Jordan	Performance of wind powered water pumping systems

In similar investigation, Badran [126] studied the performance of WEWPSs under the meteorological conditions of Jordan. Jordan has water wells possessing a variety of depths. Most of the Jordanian wells can be utilized by using wind energy resources. This type of energy is most suitable for satisfying the basic energy needs for remote desert areas in Jordan. WEWPSs are more reliable than diesel systems due to the lower maintenance, the auto stop features in the case of failures and the safe and environment friendly operation. Camocardi et al. [127] presented the operation of a new autonomous wind energy conversion system used for water pumping. It consists of a wind turbine with a brushless doubly fed induction generator (BDFIG) electrically coupled with a squirrel cage induction motor and a centrifugal pump. The absence of slip rings in the BDFIG and the possibility of eliminating the gearbox will increase the system reliability and reduce the maintenance and operational costs. Their proposed configuration with direct generator–load electric coupling and auxiliary stator control reduces the converter size and the cost of the whole system, which improves the performance. Rehman and Sahin [128] utilized wind energy to power small capacity wind turbines with a capacity of 1–10 kW for three different meteorological conditions of Saudi Arabia. It has been reported that an annual total water pumping capacity of 30,000 m^3 is possible from a depth of a total dynamic head of 50 m when using 2.5 kW. Cost savings of approximately 20% were reported by increasing the hub height from 15 m to 40 m.

4.3. Economic aspects of WEWPSs

The operating costs of WEWPSs are composed of the system cost, the initial installation cost and the operating and maintenance costs [129]. The system cost includes the cost of the complete system including the tower, the wiring, the conditioning unit, the water pump and the sales tax. The installation cost includes cost of the land and the charges for delivery and installation in the site. The annual operating and maintenance cost was assumed to be 3% of the initial system cost. The maintenance cost includes charges for painting the windmill once every 6 years and the cost of the replacement of pump valves and pumps washers once every four years. The total installation cost can be expressed as a function of the rated electrical capacity of the wind system. In general, the cost of the wind turbine decreases with an increase in the machine capacity. The cost of energy generated by the wind turbine is given by the following equations.

$$\text{Annual cost} = \frac{\text{initial cost}}{\text{Expected life (in years)} + \text{annual operating and manitenance cost}} \tag{3}$$

$$\text{Cost of energy per kW h} = \frac{\text{annual cost}}{\text{annual energy output}} \tag{4}$$

4.4. Environmental impacts of WEWPSs

The following major environment impacts of WEWPSs are as follows:

i. Wind turbines cause noise mechanically and aerodynamically [130,131].
ii. The visual impact of wind turbines varies according to the wind energy technology such as color, size, distance from the residences and shadow flickering [132–134].
iii. Wind turbines indirectly contribute to global climate change [135].
iv. Wind energy systems have negative impacts on animals and birds [136].
v. Shadow flicker from wind turbines [137].

4.5. Limitations of WEWPSs

The major limitations of WEWPSs are

i. WEWPSs are more expensive compared to SPWPSs [138].
ii. The velocity of wind is not consistent, which may affect the performance.
iii. The losses in WEWPSs are greater than those in SPWPSs. Thus, maintenance is required for mechanical components.
iv. The wake effect is a complex issue to locate the wind turbines [139].
v. The speed of the turbine reduces the wind velocity if the turbines are closely located in a wind farm, which may affect the output of the wind turbine [140].
vi. WEWPSs occupy agriculture lands.

5. Producer gas or biogas dual fuel engine pumps

Limited investigations have been reported on producer gas and biogas duel fuel engine based water pumping systems. In this section, an overview of the reported investigations is given.

5.1. Working principle of BWPSs

A biomass gasifier water pumping system consists of a biomass gasifier (with a cooling and cleaning system) and a dual fuel powered diesel engine coupled with a centrifugal pump. Gasification is a process of converting solid/liquid fuel into gaseous fuel, known as producer gas, without leaving any solid carbonaceous residue. The producer gas is a mixture of 18–22% carbon monoxide, 15–19% hydrogen, 1–5% methane and 45–55% nitrogen with a calorific value of approximately 1100 kcal/kg. This producer gas can be used in dual fuel diesel engines by replacing approximately

65–70% of diesel [7]. Biomass gasification can be effectively utilized for decentralized power generation and thermal applications. The block diagram of a producer gas source dual fuel engine is depicted in Fig. 10.

Similarly, biogas is also used as a fuel in internal combustion engines for water pumping applications. Farmers having more than 10 cattle can install a biogas generation unit to provide biogas. The dung produced by cattle can be utilized to produce biogas, which is used to power the internal combusting engines for irrigation applications. The block diagram of biogas source duel fuel engine water pumping system is illustrated in Fig. 11.

5.2. Performance of BWPSs

Only a few studies have been reported on the use of biomass for water pumping applications due to the poor calorific value of biomass fuel [141–143]. Purohit and Kandpal [143] studied the techno economic feasibility of BWPSs in India. The economic figures of merit such as the discounted payback period, the net present value, the benefit to cost ratio and the internal rate of return were estimated. It has been noted that the use of BWPSs are financially unattractive in the case of the electricity substitution. The use of producer gas-driven dual fuel engine pumps makes financial sense in locations where the biomass feedstock is freely available. The use of producer gas-driven dual fuel engine pumps will make the systems financially more attractive compared to photovoltaic and wind turbine pumps. The economic performance indicators are higher in both cases (i.e., diesel and/or electricity substitution) than the financial performance indicators, thus justifying the economic feasibility of community biogas based water pumping systems.

5.3. Economic aspects of BWPSs

The total cost of BWPSs includes the initial capital investment and the costs of the system, installation, operation, and maintenance [144]. The system cost is composed of the costs of the gasifier unit and the dual-fuel engine–pump. The installation cost includes the costs of civil erection. The operational cost of a biomass-gasifier-based power generation system is composed of the cost of the inputs (biomass, diesel and lubricants) to the system and the manpower required to operate the system. The maintenance cost of the biomass gasifier is assumed to be 5% of the cost of gasifier mainly used in the periodical replacement of the combustion cone, the air nozzle and the grate [144]. For the diesel engine pump set, the periodic replacement of the air filters, the diesel filters and the lubricant oil filters is required for the engine after every 5000 h of operation in addition to the cost of lubricants. The maximum annual repair and replacement cost was assumed to be 10% of the capital cost of the diesel engine pump set.

5.4. Limitations of BWPSs

The following major limitations are identified with BWPSs:

i. The potential of BWPSs depends on many factors such as resource availability, the requirements, the affordability and the tendency to invest in BWPSs.
ii. The operating and maintenance cost of BWPSs are high compared to other REWPSs.
iii. Bio fuels may form corrosion in the engine components.
iv. There are more energy losses during the transmission of power from engine to the pump.
v. The performance of the engines powered by biomass fuels is significantly affected.
vi. Biomass fuels have a very low calorific value, which affects the performance of the engine.

6. Studies on HREWPSs

Very few investigations have been reported on HREWPSs. In this section, an overview of the reported investigations is discussed.

6.1. Working principle of HREWPSs

HREWPSs integrate two or more forms of energy sources. Water pumping systems designed based on one form of renewable energy resources have the drawback of being oversized due to the lack of availability. Hybrid systems depend on more than one energy source and require the system to operate more flexibly and reliably [8,9]. The solar–wind hybrid form of RESWPS is schematically illustrated in Fig. 12. Limited research investigations have been reported with HREWPSs, which are listed in Table 9.

6.2. Performance of HREWPSs

Vieira and Ramos [145] optimized the operation of hydro-wind HREWPSs. It has been concluded that it is possible to save up to 47% of the energy costs. They also reported that hydro-wind HREWPSs will reduce CO_2 emissions. The use of hybrid RESs in a balancing way will allow the stabilization of the energy distribution. Similarly, Habib et al. [146] developed an optimization procedure to size photovoltaic–wind HREWPS to produce

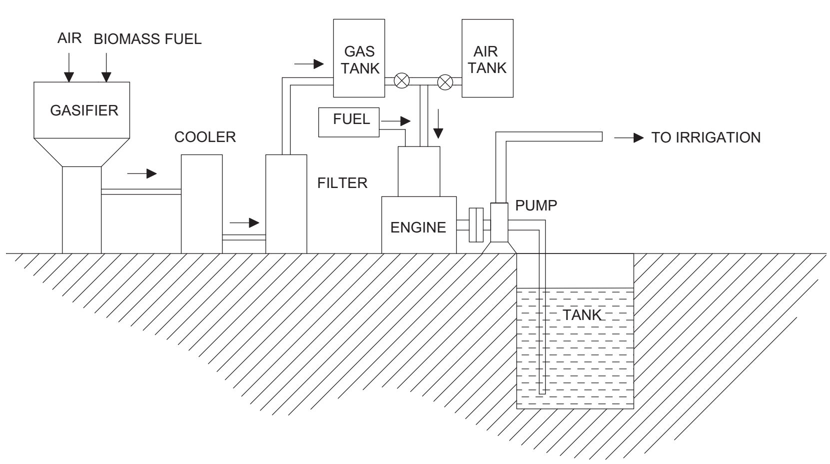

Fig. 10. Layout of biomass water pumping systems [7].

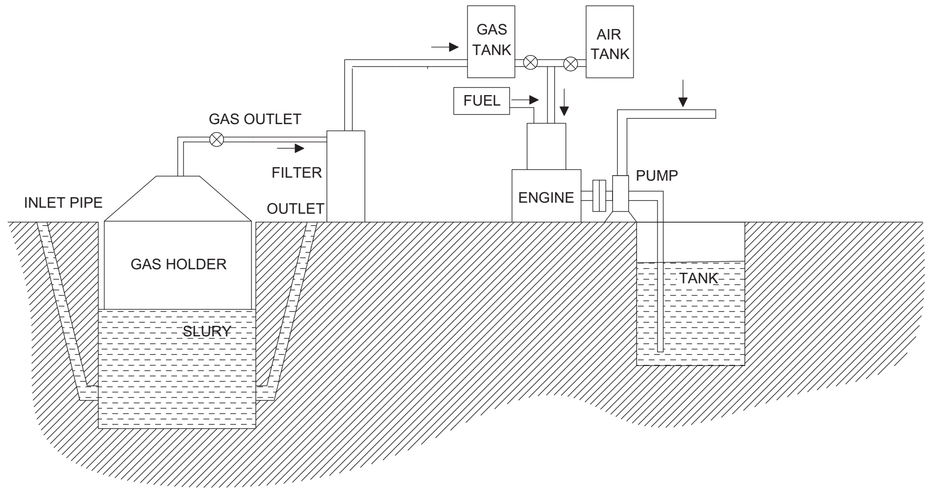

Fig. 11. Layout of biogas water pumping systems.

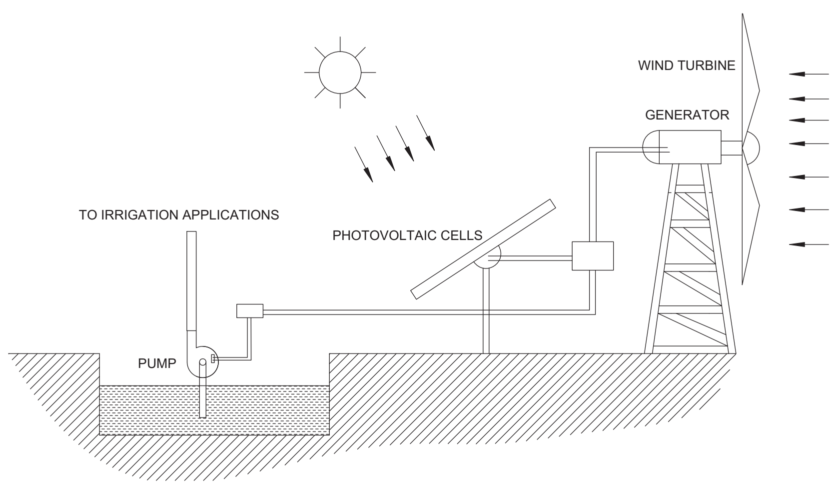

Fig. 12. Layout of hybrid energy source water pumping systems.

Table 9
Hybrid form of energy for water pumping systems.

Authors [Reference]	Country	Hybrid form of energy used
Vieira and Ramos [145]	Portugal	Hydro–wind energy
Habib et al. [146]	Saudi Arabia	Solar–wind
Vick and Neal [147]	USA	Solar–wind

a constant load of 5 kW in the Dhahran area of Saudi Arabia. The analysis reported that a hybrid system power output can be optimized to suit specific applications with variable power loads. The results indicated that the optimal solar–wind ratio resulted in a minimum capital cost of approximately 70%. In a similar study, the performance of a wind turbine and solar photovoltaic powered water pumping were investigated individually and combined as a hybrid system [147]. The peak pumping efficiencies at a 75 m pumping depth of the solar–wind hybrid system were reported to be 47%, 51% and 55% for different hybrid configurations of wind turbine/320 W photovoltaic array, wind turbine/480 W photovoltaic array, and wind turbine/640 W photovoltaic array, respectively. They also developed a controller to improve the performance of the HREWPS. The voltage from the wind turbine is matched with the voltage from the photovoltaic array when the power from the photovoltaic array can be added to wind turbine. During periods when the voltage from the photovoltaic array is below the useable range for the pump and there is sufficient voltage from the wind turbine, the controller will adjust the voltage of the wind turbine to operate the pump efficiently without power from the photovoltaic array. Likewise, when the wind turbine voltage is below the useable range, only photovoltaic array power will be used to power the pump.

7. Performance comparison of different RESWPSs

In this section, the various forms of RESs used to power the water pumping systems are compared.

7.1. Performance comparison of SPWPSs and diesel powered systems

Mahmoud and Nather [148] studied the feasibility (in remote areas of Egypt) of using SPWPS for irrigation applications and compared them with diesel water pumping units by considering the parameters affecting the costs and the present value of the systems. It was reported that photovoltaic-battery backup systems can be used efficiently compared to diesel water pumping systems. Similarly, Kelley et al. [149] presented the technical and economic

feasibility of a solar-powered irrigation system and compared it with diesel and electrical grid connected water pumping systems. The feasibility of the solar photovoltaic source irrigation system was calculated as a function of location, which includes climate data, the aquifer depth and the cost, including local political policies such as carbon taxes. It has been reported that SPWPSs for irrigation are technically and economically feasible, if sufficient land space for installing the solar photovoltaic solar array is available. Chueco-Fernández and Bayod-Rújula [150] examined and compared the cost-effectiveness to power the pumping systems in remote areas in northern Chile by using solar photovoltaic systems, diesel engines and grid extensions. In their work, variables such as the distance to the power grid, the voltage, the prices of electricity and fuel, and the required investments were considered. The comparison was made for a wide range of variable values, distances and pumping requirements. It has been reported that SPWPSs are more cost-effective than diesel engines or grid extension to power small and medium pumping systems. For large scale pumping systems, the diesel engines or grid extension are generally cost-effective. Nevertheless, the increase of fuel and energy prices and the decrease of photovoltaic costs make the solar photovoltaic water pumping systems more feasible.

In another work, Odeh et al. [151] compared the economic viability of SPWPS (2.8 kWp to 15 kWp) with that of a diesel water pumping system. In SPWPSs, the water unit cost is affected by the system productivity, the capital investment, the interest rate and the operating cost, whereas, in diesel pumping systems, the cost is affected from highest to lowest effect by the system productivity, the operating cost, the capital investment and the interest rate. Because of its high capital cost, SPWPSs were limited to small-scale applications. Currently, the use of medium scale systems up to 11 kWp is not only becoming feasible but can also be introduced as investment profitable projects. Al-Smairan [152] compared the performance of SPWPSs with diesel engine water pumping systems under the meteorological conditions of Jordon. It has been reported that SPWPSs are cost effective compared to diesel engine water pumping systems. However, the operating and maintenance costs of SPWPSs makes the systems reasonable compared to diesel engine-based water pumping systems.

7.2. Performance comparison of WEWPSs and diesel powered systems

El-Dam [153] analyzed the economic feasibility of diesel and WEWPSs under the meteorological conditions of Sudan. It was concluded that commercial manufacturing of the local windmills is more economical than using imported windmills and diesel pumps for water pumping applications. Cloutier and Rowley [154] studied the feasibility of REWPSs under the meteorological conditions of Nigeria. It was reported that the REWPSs system is an attractive option both economically and logistically in comparison to fossil-fuel based water pumping systems. Although the initial capital investment of REWPSs is significantly greater compared to conventional fossil fuel based water pumping systems, their net present cost over a 20-year project life is only a fraction of that for the conventional fossil fuel based water pumping system because of the increase in ongoing fuel costs. The SPWPSs have lowest overall cost when comparing the three RESs and are the best options for a water pumping system.

7.3. Performance comparison of BWPSs with diesel water pumping systems

Tripathi et al. [155] compared the unit cost of water discharged using biomass gasifier based water pumping systems (at a biomass price of INR 0.50/kg) with two conventional water pumping methods such as a diesel engine pump set (at a diesel price of INR 12 per liter) and an electric motor pump set (at the rate of INR 3.0/kW h) in India. The layout of the biomass gasifier used in their work is illustrated in Fig. 13. Their reported results showed that the biomass gasifier based water pumping system would become financially competitive with diesel engine and electric motor based water pumping methods only in regions where sufficient biomass resources are available.

7.4. Performance comparison of SPWPSs and wind and diesel powered systems

Ramos and Ramos [156] compared the performance of stand-alone (solar and wind hybrid energy system) and grid-connected water pumping systems. In the grid-connected system, two solutions were analyzed, one with a water turbine and another without a water turbine. To implement a water turbine, a larger water pump was needed to pump the required water for energy generation. For the case analyzed, the system without a water turbine proved to be more cost-effective because the energy tariff is not competitive and due to the cost of water turbines. In another work, Hammad [157] compared the economics of water pumping by different methods such as photovoltaic, wind and diesel powered water pumping systems. It was reported that the cost of water pumped by photovoltaic powered and wind energy powered pumping systems is lower than diesel engine based pumping systems. He suggested that SPWPSs are more suitable for low capacities.

7.5. Performance of SPWPSs, WEWPSs and HREWPSs

Skretas and Papadopoulos [158] proposed the systematic design approach for three water pumping systems, SPWPSs, WEWPSs and HREWPSs, using the measured meteorological data for the city of Xanthi, Greece. It has been reported that the performance of HREWPSs was better than that of WEWPSs and SPWPSs. They also concluded that HREWPSs are suitable for small capacity water pumping. Bouzidi [159] studied the viability of two options (solar or wind energy sources) for water pumping systems in the Algerian Sahara regions. It was reported that the cost per cubic meter of water produced by the wind pump system is cheaper than that produced by the photovoltaic system. The authors proposed wind energy as an alternative solution for water pumping due to its technical and economic feasibility compared to solar photovoltaic water pumping systems.

7.6. Cost comparison of various RESWPSs

The cost analyses of various RESWPSs are compared in Table 10.

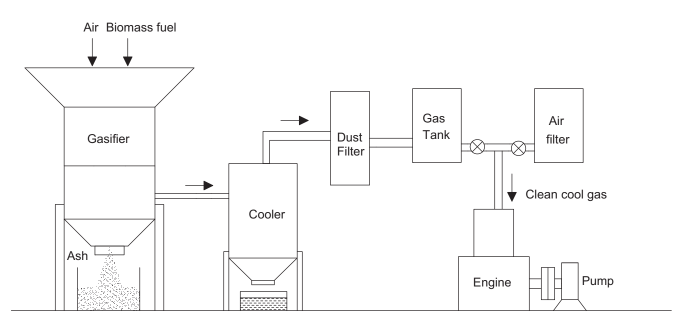

Fig. 13. Schematic view of BWPSs [155].

Table 10
Cost analysis of various RESWPSs in Coimbatore, India.

RESWPSs	Capacity	Head (m)	Working time per day (h)	Initial cost (INR)	Operation and maintenance cost (INR) per year	Life years
SPVWPSs (Submersible pumps)	5 HP – 3Phase – AC	20 m	8	370,000	2,000	20
WESWPSs (Submersible pumps)	5 HP – 3Phase – AC	20 m	8	525,000	*	20
BWPSs (including gasifier) (Surface pump)	5 HP	20 m	8	70,000	*	20
Solar–wind HRESWPSs (Submersible pump)	5 HP – 3Phase – AC	20 m	8	950,000	*	20
Diesel Engine based systems (Surface pump)	5 HP	20 m	8	40,000	161,800	20
Electrical grid connected systems (Submersible pump)	5 HP – 3Phase – AC	20 m	8	22,000	54,020	25

*The portable WESWPSs, BWPSs and HRESWPSs suitable for 5 HP are not available in Coimbatore region
Cost of diesel is INR 52/l,
Cost of electricity per kW h is INR 5, 1 US$ = 54.82 INR (on 05.04.2013).

8. RESWPSs—Indian scenario

In India, approximately 58% of the geographical area can potentially be solar hot spots in the country with more than 5 kW h/m^2/day of annual average global insolation [160]. The solar energy availability in India could fulfill the increasing power requirements in a decentralized, efficient and sustainable manner in the form of solar photovoltaic energy conversion systems. Similarly, India has a large coastal area with abundant sources of wind energy, which supports water pumping in agriculture sectors. The overall potential of wind energy in India is approximately 48,500 MW. Of the total potential, 12,009.48 MW has been connected for providing energy [161]. Biomass is another major RES for the effective cleaning of environment by absorbing CO_2. The commonly used biomasses in India are wood, charcoal, dried dung, bagasse, rice husk, straw, coffee waste and other agriculture waste. The geographical conditions of India can create an ideal environment for biomass development due to the sufficient amount of solar radiation and precipitation in the country. Purohit and Kandpal [162] presented future dissemination levels of REWPSs in India predicted by the logistic diffusion model depicted in Figs. 14–17. The renewable energy water pumping technologies in India are influenced by many techno-economic factors including the financial incentive schemes provided by the central and state governments. According to Figs. 14–17, the number of REWPSs installations will increase drastically during the next decade. In India, SPWPSs are estimated to have the highest utilization potential followed by WPWPSs. Other modes of water pumping systems are not still commercialized in India due to their technical limitations.

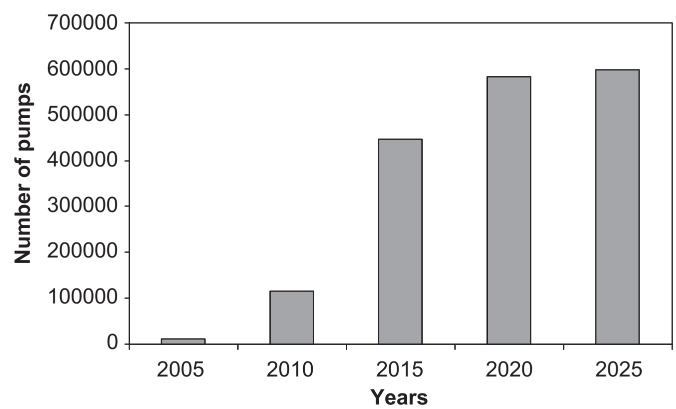

Fig. 14. Projected dissemination of SPWPSs [162].

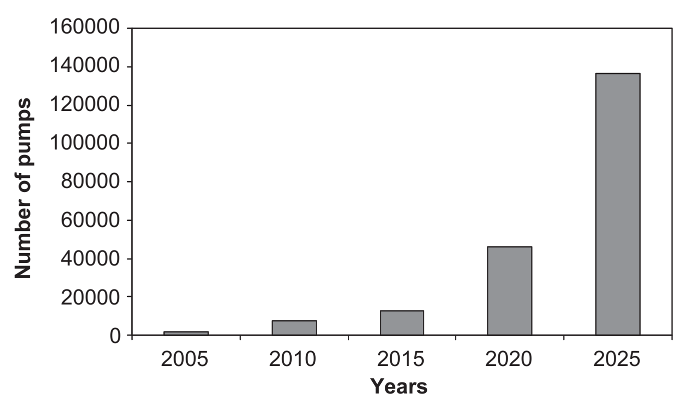

Fig. 15. Projected dissemination of WEWPSs [162].

9. Further research needs

From the cited literature, the following research extensions are identified in the field of RESWPSs:

i. Development of new hybrid forms of REWPSs for irrigation applications.
ii. Clean development mechanism analysis of RESWPSs [163].
iii. Optimization of the tilt angle of photovoltaic panels for different meteorological conditions [164].
iv. Cooling of photovoltaic panels using phase change materials.
v. Cooling of photovoltaic panels using specialized heat sinks.
vi. Investigations with photovoltaic panels covered with glazing materials to reduce the dust accumulation.
vii. The integration of phase change materials with STWPSs to improve their efficiency.
viii. Development of new working fluids for STWPSs.
ix. Feasibility of STWPSs for irrigation applications.
x. Reduction in power losses of WEWPSs [124].
xi. The compatibility of biomass fuels in I.C. engines requires further investigation [165].
xii. The development of additives to reduce the corrosion in engine cylinders [165].
xiii. The characterization of new biomass fuel used for water pumping applications.
xiv. Further research studies are required to reduce the production cost of biomass fuels [166].
xv. The environmental benefits offered by BWPSs must be popularized [167].
xvi. Techno-economic feasibility of REWPSs.
xvii. Artificial intelligence based modeling of RESWPSs.
xviii. Second law (exergy) analysis of REWPSs to identify the inefficient components [168].
xix. Optimization of the tilt angle of solar photovoltaic panels.

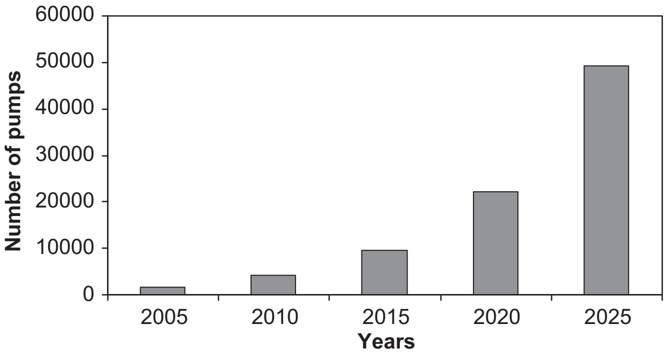

Fig. 16. Projected dissemination of biogas powered water pumping systems [162].

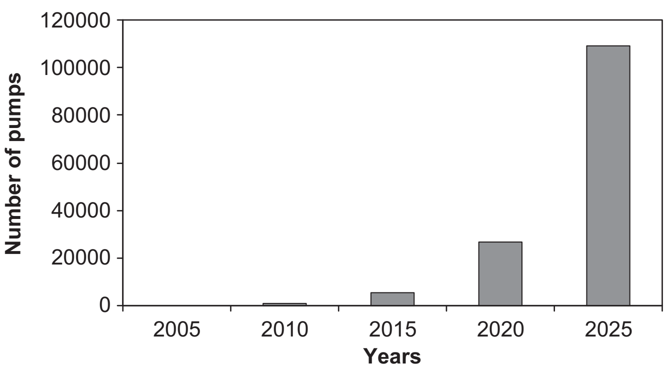

Fig. 17. Projected dissemination of producer gas powered water pumping systems [162].

10. Conclusion

Researchers from various regions of the world have conducted many experimental and theoretical investigations on REWPSs. More than one hundred published articles related to RESWPSs were reviewed and briefly summarized. The published literature addressed in this paper confirmed that RESWPSs are identified as an alternative source for replacing conventional pumping methods. The integration of RESs with water pumping systems plays a major role in reducing the consumption of conventional energy sources and their environmental impacts, particularly for irrigation applications. The SPWPSs are the most widely used RESWPSs for irrigation and domestic applications, followed by WEWPSs. The solar thermal and biomass water pumping systems are less popular due to their low thermal energy conversion efficiencies. The limitations faced by RESWPSs were identified and listed. The research openings in the field of RESWPSs were also highlighted. This review work provides a good background for researchers pursuing their research in the field of RESWPSs.

The greater potential of solar and wind energy availability in India means that a solar photovoltaic-wind hybrid energy system for water pumping applications should be developed. The authors developed a solar photovoltaic-wind energy HREWPS and tested its performance under the meteorological conditions of Coimbatore city in India. The authors also propose its thermodynamic and economic feasibility for irrigation applications. Such research investigations are in progress in the research laboratory of the authors.

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